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The Interstellar Conspiracy

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What if . . .

If we were designing a human-carrying starship that could be launched in the not-too-distant future, it would almost certainly not use a warp drive to instantaneously bounce around the universe, as is done in Isaac Asimov's classic *Foundation* series or in episodes of *Star Trek* or *Star Wars*. Sadly, those starships that seem to be within technological reach could not even travel at high relativistic speeds, as does the interstellar ramjet in Poul Anderson's *Tau Zero*. Warp-speeds seem to be well outside the realm of currently understood physical law; proton-fusing ramjets may never be technologically feasible (Matloff, 2000). Perhaps fortunately in our terrorist-plagued world, the economics of antimatter may never be attractive for large-scale starship propulsion (Mallove and Matloff, 1989).

But interstellar travel will be possible within a few centuries, although it will certainly not be as fast as we might prefer. If humans learn how to hibernate, perhaps we will sleep our way to the stars, as do the crew in A. E. van Vogt's *Far Centaurus*. However, as discussed in a landmark paper in *The Journal of the British Interplanetary Society*, the most feasible approach to transporting a small human population to the planets (if any) of Alpha Centauri is the worldship (Bond and Martin, 1984). Such craft have often been featured in science fiction. See for example Arthur C. Clarke's *Rendezvous with Rama*, and Robert A. Heinlein's *Orphans of the Sky*.

Worldships are essentially mobile versions of the O'Neill (1974, 1977) free-space habitats. Constructed mostly from lunar and/or asteroidal materials, these solar-powered, multi-kilometer-dimension structures could house 10,000 to 100,000 humans in Earth-approximating environments. Artificial gravity would be provided by habitat rotation, and cosmic ray shielding would be provided by passive methods, such as habitat atmosphere and mass shielding, or magnetic fields (Johnson and Holbrow, 1977). A late 21st century space-habitat venture might support itself economically by constructing large solar-powered satellites to beam energy back to Earth.

But how might a multi-billion-kilogram space habitat be propelled if its inhabitants choose to attempt an interstellar migration with antimatter, ramjets and warps ruled out? A landmark paper by Dr. Anthony Martin, who currently edits *The Journal of the British Interplanetary Society*, addresses this issue (Martin, 1984). Gravity assist maneuvers using the giant planets may be used to fling a spacecraft towards the stars, as has been demonstrated by our first extrasolar probes, *Pioneer 10/11* and *Voyager 1/2*. Unfortunately, this is a time-consuming technique – about 70,000 years would be required by the fastest of these vehicles to reach Alpha Centauri, if any of them happened to be traveling in that direction.

If interstellar migrants intend to cross the 40 trillion kilometers between the Sun and Alpha Centauri within a millennium or so, there are only two propulsion systems that currently appear promising. These are nuclear-pulse propulsion and the ultra-thin solar-photon sail unfurled as close to the Sun as possible.

The nuclear-pulse rocket, which is derived from the DoD/NASA *Orion* Project of the 1960s, would ignite nuclear or thermonuclear "devices" as close as safely possible to the spacecraft. A properly shielded combustion chamber would reflect explosion debris, thereby propelling the spacecraft by Newton's Third Law. As demonstrated by Dyson (1968), a thermonuclear Orion could propel a worldship on a voyage of less than 1,300-year duration to Alpha Centauri, if the world's nuclear powers agreed to sacrifice most of their thermonuclear arsenals. Fat chance!

A somewhat sanitized nuclear-pulse starship, Project *Daedalus*, was studied by a British Interplanetary Society team during the 1970s (Bond *et al*, 1978). *Daedalus* would have been propelled by electron beam-initiated explosions of fusion micropellets. The fusion fuel of choice was a combination of deuterium and helium-3. Although theoretically capable of accelerating a large starship to 10 percent of the speed of light (0.1c), the *Daedalus* concept was hampered by the terrestrial rarity of helium-3. Unless we can mine this isotope from a cosmic source – the solar wind, lunar regolith, or giant-planetary atmosphere – *Daedalus* would not be a practical solution to starflight.

Another disadvantage to nuclear-pulse propulsion is scaling. No matter whether the payload is a billion-kilogram worldship or a 10-kilogram microprobe, the propulsion system will still be enormous.

The remaining interstellar option – the solar sail – is quite scalable, which is a good thing for the budgets of present-day sail experimenters. The concept of interstellar solar-sailing was developed independently by two teams in the late 70s and early 80s. Chauncey Uphoff of NASA's Jet Propulsion Laboratory (JPL) in Pasadena, California, considered this as an alternative propulsion method for the NASA Thousand Astronomical Unit (TAU) extra-solar probe study, but his work was only incorporated into that study as an "unpublished memo" (Jaffe *et al*, 1980). In a series of papers beginning in 1981, Gregory Matloff and Eugene Mallove presented various aspects of this propulsion option in the peer-reviewed literature (Matloff and Mallove, 1981, 1983).

As described in the cited references, an interstellar solar sail would approach the Sun as closely as possible with the sail either directed away from the Sun or otherwise protected from solar-radiation pressure prior to perihelion. At perihelion, the sail would be partially or fully unfurled and exposed to sunlight, accelerating the solar sail by the radiation pressure of solar photons.

Analysis revealed that if ultra-thin (20-30 nm), space-manufactured, all-metal sails are used with perihelion passes that are as close to the Sun as physically possible (within about 0.04 AU of the Sun's center) and if the cables joining sail to payload approximate the tensile strength of an industrial diamond, even large payloads could be accelerated in this manner towards Alpha Centauri on trajectories requiring about 1,000 years. After acceleration (at 1 g or higher), cable and sail could be wound around the habitat section to provide extra cosmic ray shielding. Assuming the space-manufactured sail has a very long lifetime in the galactic environment, sail and cables could also be used again for deceleration at the destination star system (Matloff, 2000a).

Of course, we could not construct such a starship today. But a NASA project – the In-Space Propulsion (ISP) Technology Project – is gaining knowledge about sail films and structures, high-acceleration operation of gossamer structures in space, and the application of ultra-thin filaments that could lead to the development of sail cables. Since this capability is being developed to support modestly-funded science missions, not voyages of interstellar colonization, the work of ISP may be thought of as an "interstellar conspiracy", by which means humanity is developing an interstellar capability almost as an afterthought.

What is . . .

The In-Space Propulsion (ISP) Technology Project and its Products?

Managed at the NASA Marshall Space Flight Center in Huntsville, Alabama, the In-Space Propulsion (ISP) Technology Project is an outgrowth of the NASA "Interstellar Initiative" of the late 1990s. The initial ISP research concentration was on propulsion systems, such as current-technology Earth-launched solar sails unfurled 0.2 – 0.3 AU from the Sun, that would enable *in situ* exploration within a few hundred AU of the Sun on missions of a few decades duration (Johnson and Leifer, 2000). The purview of ISP has since been expanded to include propulsion systems that could enable or enhance all scientific space missions under consideration by the NASA Science Mission Directorate with destination above low-Earth orbit (LEO).

Most technologies considered by ISP researchers are approaching flight readiness, although some attention in the past was devoted to more speculative, higher-risk propulsion concepts with potentially high payoffs, such as plasma sailing (see *Analog*, Jan/Feb 2004 Fact Article). A prioritization system has been developed by ISP to match in-space propulsion technologies with planned or proposed space missions in an effort to recommend funding levels for maturing the most promising technologies.

As well as the solar-photon sail, five in-space propulsion technologies dominate the ISP research spectrum. These include advanced chemical propulsion, advanced solar electric propulsion (SEP), aerocapture, solar thermal propulsion (STP) and tethers.

(I) *Advanced Chemical Propulsion*

Today's chemical rockets are approaching their practical and physics-driven limits. To maximize the scientific return from space probes designed to descend for landings on planetary surfaces or ascend from such surfaces to return samples to Earth, a number of improvements to chemical rocket technology are under study and development.

Goals of this research include increased performance and safety, reduction in propellant storage uncertainties, and improved system efficiency. As well as advanced chemical fuels, ISP researchers are investigating improvements in cryogenic fluid management to improve the efficiency and handling of cryogenic components. Another area of ISP chemical rocket investigation is the reduction of the mass and complexity of structures utilized to carry and transfer propellants. While advanced chemical propulsion systems would not be applicable to interstellar voyages, this evolutionary technology could enable more ambitious exploration of our Solar System.

(II) *Advanced Solar Electric Propulsion (SEP)*

Also called the "ion drive", solar electric propulsion works by using collected solar energy to first ionize and then accelerate propellants to exhaust velocities considerably higher than the 4.5 kilometers per second (km/sec) exhaust velocity of state-of-the-art chemical fuels. The exhaust velocity of the ion engine aboard the highly successful NASA Deep Space 1 probe was about 30 km/sec. The best SEP propellants are inert gases such as xenon and krypton.

Although high velocities are possible using SEP (and its nuclear cousin NEP), ion drives have low thrust and will always be utilized in space, never for Earth-to-orbit transportation. A number of improvements under consideration by ISP promise to increase the performance of future SEP-propelled interplanetary probes.

One approach seeks to increase SEP power levels to the multi-kilowatt (kW) level. Laboratory demonstrations of Hall-effect thrusters are currently underway. This will allow efficient SEP operation on missions significantly more challenging than previously flown.

Research is also underway on methods for increasing the exhaust velocity of next-generation SEP to around 50 km/sec. Because of the higher exhaust velocity, fuel requirements for a given mission using next-generation SEP will be reduced, which also promises to increase the scientific payload mass.

Additional research is underway to increase the efficiency and lifetime of ion thrusters. This will result in longer-duration SEP missions farther from the Sun, some of which may serve as interstellar precursors.

(III) *Aerocapture*

Aeroassist technology has been used since the early days of space travel. Every returning capsule and shuttle has applied the atmosphere as a drag brake and thereby greatly reduced the requirement for reentry fuel.

A related technology is aerobraking, whereby a spacecraft in an elliptical orbit around a planet with an atmosphere dips into that planet's atmosphere repeatedly, to gradually circularize the orbit and decrease the spacecraft's distance from the planet.

An interplanetary spacecraft will be able to use the new technology of aerocapture to become a satellite of a planet by performing a single pass through the atmosphere.

Current aerocapture research under ISP emphasizes integrating a low-mass aeroshell with a thermal protection system and the development of aerocapture instrumentation. Various advanced aerodynamic decelerators are under consideration for aerocapture missions, including rigid structures, trailing ballutes, attached ballutes and inflatable aeroshells.

Aerocapture is a fast maneuver, with a spacecraft decelerating from interplanetary to orbital velocity. Decelerations in some cases are higher than 1 g, and knowledge of the destination planet's atmospheric profile is required to optimize the aerocapture trajectory.

Other than the Earth, a number of Solar System bodies have atmospheres dense enough for aerocapture. These include Venus, Mars, Jupiter, Saturn, Titan, Uranus and Neptune.

Advances in aerocapture technology could quicken the development of aeroshells of lower mass and greater thermal tolerance. One can imagine advanced aerocapture missions decelerated by Neptune's atmosphere for rendezvous with Kuiper Belt Objects (KBOs) near the giant planet (Matloff, 2000b, Matloff and Taylor 2003). As aeroshell mass is reduced, the propulsion mass will also decrease since aerocapture greatly reduces the requirement for deceleration fuel.

(IV) *The Solar Photon Sail*

ISP solar sail research concentrates upon near-term Earth-launched solar sails with a typical areal density of 0.015 kg/m^2. Operational near-term sails will be stowed for launch and unfurled in space. Unlike the ultimate space-manufactured metallic sails, these are generally tri-layered. A plastic substrate is sandwiched between a reflective layer facing the Sun and a rear emissive layer that radiates absorbed solar energy.

As well as investigating low-mass materials and supporting structures, ISP sail researchers are considering methods of propellantless guidance, navigation and control and developing relevant computer codes. Ground validation of deployment techniques for sub-scale sails is currently underway.

The solar sail requires no propellant (since thrust is provided by linear momentum transferred from impacting solar photons) and has no environmental impact. Unless efficient methods of power beaming are developed (Forward, 1984), sail technology will find most application on inner-Solar System missions where sunlight is most intense.

Near-term missions that may be enabled by the solar-photon sail include pole sitters permanently situated over high-latitude locations (McInnes, 1999) and constellations of solar observatories situated sunward of the Earth on long-duration missions to monitor space weather.

Although thin-film and inflatable structures have been unfurled in space, no dedicated solar sail mission has flown to date. In 2005, the *Cosmos-1* test sail is scheduled for unfurlment in low-Earth orbit (LEO) by The Planetary Society of Pasadena, California. The first NASA-launched sail may fly before 2010.

(V) *Solar Thermal Propulsion (STP)*

Solar Thermal Propulsion is another in-space propulsion system that can live off the interplanetary land. This propulsion technology operates by focusing sunlight on a gaseous propellant, such as hydrogen (Shoji and Frve, 1988 and Grossman and Williams, 1990). Concentrated sunlight is focused upon an absorbing heat-exchange system for transfer to the propellant. For efficient operation, the propellant is heated to temperatures as high as 2780 Kelvin. Exhaust velocities of the heated fuel are intermediate between chemical and solar electric propulsion, typically 8 to 10 km/sec. Although STP does not have sufficient thrust for ground-LEO operations, the technology could transfer a payload between LEO and geosynchronous orbit (GEO) in about 30 days.

ISP research on this propulsion system deals with a number of issues, including solar-concentrator design. Both inflatable and rigid concentrators are under consideration, although inflatable concentrators are currently favored.

(VI) *Tethers*

Of all the ISP technology products, the tether seems the most magical. Imagine – all an Earth-orbiting spacecraft has to do to raise its orbital height is to unwind an appropriately designed long, thin cable! Both electrodynamic (ED) and momentum exchange/electrodynamic reboost (MXER) tethers are under study by ISP researchers.

Electrodynamic tethers have been described by Samanta *et al* (1992), Beletskii and Levin (1993) and Estes *et al* (2000). They have also been demonstrated in space by the NASA Tethered Satellite System mission in 1996. To reboost a LEO spacecraft using an ED tether, a long conducting strand is unraveled from the spacecraft and oriented with the low end attached to the spacecraft. Electrons are collected from the Earth's upper ionosphere near the position of the spacecraft. Powered by energy obtained from the spacecraft's solar array, the collected electrons are pushed up the tether and emitted at a higher altitude than the spacecraft's orbit. The resulting electrodynamic force on the tether's unidirectional current adds energy to the spacecraft's orbit, thereby raising the orbital height.

As described by Sorensen (2001), the MXER tether is a hybrid ED/momentum-exchange tether. A rotating momentum-exchange tether can increase a payload's orbital energy by grappling the payload at the low point of the tether's rotation and releasing it at the high point. However, the orbital energy of the tether itself decreases during this maneuver, and its orbital height is consequently lowered.

A rotating MXER tether has its rotation timed so that the tether tip is oriented below the tether-system center-of-mass and is swinging backwards at the perigee of its elliptical orbit. A payload from a LEO or sub-orbital launch is captured by a grapple on the lower tether tip at zero relative velocity and released at the high point of the tether's rotation. In theory, payloads could be accelerated to escape velocity in this fashion.

Left to its own devices, the MXER tether's orbit would decay after each payload capture and release. But if the MXER tether can also operate as an ED tether, electrodynamic forces on the unidirectional current flow can be used to raise the tether-station's orbit.

Much analytical work remains to be done to demonstrate the feasibility of this concept. But the MXER tether has the potential to revolutionize interplanetary space travel.

Ad Astra

Implementing an Interstellar Capability

At this point in space history, routine Earth-to-orbit travel remains a major challenge. But the Moon, Mars and more remote destinations draw our attention outward. The ISP research efforts on the technology products described will positively impact the development of the space infrastructure required to support an expanding interplanetary and, ultimately, interstellar human civilization.

Certain requirements for the expansion of human civilization beyond the Earth – understanding and mitigation of space-radiation effects, determination of optimum artificial gravity levels, development of closed-environment systems, etc. -- will be satisfied by experiments aboard the International Space Station or in conjunction with the next phase of exploratory missions above LEO. These will not be further discussed in this article.

Application of ISP technology products will have many positive effects in the development of an interplanetary (and ultimately interstellar) civilization. One requirement for such a civilization is expanded knowledge of the resource base of the Solar System. Advanced chemical rocketry, solar electric propulsion, and aerocapture should result in more massive and flexible scientific payloads to acquire this knowledge.

As well as reducing the cost of orbital transfer, development of solar thermal propulsion should assist the development of space mining and construction. Focused sunlight from the STP concentrator optics will provide an intense energy source for these applications.

Advances in chemical rocket technology may lead to the construction of spacecraft components directly from extraterrestrial resources. Such construction might be implemented by Rapid Prototyping (RP), which is the three-dimensional equivalent of a Fax (Doyle, 2000). After a prototype is designed by a computer-aided design package, the RP machine quickly constructs the prototype layer by layer, conceivably using extraterrestrial resources as the feedstock. Perhaps this technique will be applied to the in-space construction of the ultra-thin solar-photon sails required for interstellar travel.

As discussed by O'Neill (1974, 1977), SEP research may lead to the development of the mass driver. These solar-powered electromagnetic catapults could transfer large quantities of material from space mines to space manufacturing facilities.

The ultimate design of robotic or crewed solar sail starships will be served by ISP research. In addition to the in-space fabrication of ultra-thin sail films, starship designers will require thin, strong cables connecting sail and payload and demonstration that the ship can operate in the high-temperature, high-acceleration environment of a close solar pass.

Finite-element computer models indicate that several sail configuration remain stable for accelerations as high as 2.5 g (Cassenti *et al*, 1996). Tethers will yield experience with the operation of cable-like structures in space. Some aeroshell designs decelerating in planetary atmospheres will simulate the near-Sun acceleration of solar sail starships.

During the summer of 2004, the ISP team witnessed video recordings of the first ground test unfurlments of NASA solar sails. It was clear to all witnesses that the idea of interstellar travel is beginning to emerge from the theoretical paper and the science fiction story into the realm of system engineering. Perhaps within the lifetimes of many *Analog* readers, humanity's first robotic interstellar emissaries will be sailing the interstellar seas. Although we will not witness them, we can dream of the ultimate expeditions to follow, which will carry people to the stars.

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Biographies:

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